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Title: METHOD AND SYSTEM FOR MODELING INTERACTION OF OBJECTS

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Method and System for Modeling Interaction of Objects

Field of the Invention

The present invention relates generally to the field of computer graphics, and particularly to collision detection and model interaction.

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Background of the Invention

While there has been significant progress in simulating collisions between rigid bodies, much remains to be done for modeling interactions between soft bodies, see Lin et al., *"Collision detection between geometric models: a survey,"* Proc. IMA Conference on Mathematics of Surfaces, 1998. Graphical techniques for representing and deforming soft bodies range from non-physical, e.g., control point-based, to physically plausible, e.g., free form deformation (FFD), to physically realistic, e.g., finite element methods (FEM), see Gibson et al., *"A survey of deformable modeling in computer graphics,"* MERL Technical Report, TR97-19, 1997.

All of these techniques require three basic operations to model interactions between soft bodies: 1) detecting collisions between deformable bodies, 2) computing impact forces when the bodies collide, and 3) determining deformation forces or contact deformation of the bodies to initialize a deformation procedure.

It is desired to perform all three operations quickly, with efficient use of memory, and more accurately than known methods. In addition, it is desired that the results

of these operations can be used by any of the know deformation techniques stated above.

Summary of the Invention

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The present invention provides a method for modeling interactions between models. A first adaptively sampled distance field having a first spatial hierarchy for a first model is generated, and a second adaptively sampled distance field having a second spatial hierarchy for a second model is generated.

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During each time step, a potential overlap region is determined using the spatial hierarchies of the first and second adaptively sampled distance fields.

When the potential overlap region is non-empty, a third adaptively sampled distance field is generated from the first and second adaptively sampled distance

15 fields using a first interaction procedure and first properties and a fourth adaptively sampled distance field is generated from the first and second adaptively distance fields using a second interaction procedure and second properties to model the interactions between the first and second models.

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Brief Description of the Drawings

Figure 1 is a flow diagram of a method and system for modeling interactions between deformable objects according to the invention;

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Figure 2a is a diagram of a physical interaction between two deformable objects;

Figure 2b is a diagram of a proximity interaction between two deformable objects;

Figure 3 is a diagram of force vectors in an overlap region of the two interacting bodies of Figures 2a and 2b;

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Figure 4 is a flow diagram of modeling interactions between deformable objects using a physical simulator;

Figure 5 is a flow diagram of modeling interactions between deformable objects
10 using multiple adaptively sampled distance fields; and

Figure 6 is a flow diagram of modeling interactions between deformable objects using adaptively sampled distance fields and a physical simulator.

Detailed Description of the Preferred Embodiment
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Introduction

We have recently described adaptively sampled distance fields (ADFs) as a data
20 structure for representing shape, and indicated that ADFs might also be useful for collision detection, see Frisken et al. *"Adaptively sampled distance fields: a general representation of shape for computer graphics,"* Proc. SIGGRAPH'00, pp. 249-254, 2000, also see U.S. Patent Application Sn. 09/370,091 *"Detail-Directed Distance Fields"* filed by Frisken et al. on August 6, 1999, incorporated herein in
25 its entirety by reference.

ADF methods adaptively sample a signed distance field of an object and store the

sample values in a spatial hierarchy, e.g., a sparse octree, for fast processing.

Methods that can operate on ADFs are described in: U.S. Patent Applications Sn.

09/810,983 *"System and Method for Generating Adaptively Sampled Distance*

Fields with Bounded Distance Trees" filed by Perry et al. on March 16, 2001, U.S.

Patent Application Sn. 09/810,839 *"Conversion of Adaptively Sampled Distance*

Fields to Triangles" filed by Frisken et al. on March 16, 2001, U.S. Patent

Application Sn. 09/811,010 *"System and Method for Modeling Graphics Objects"*

filed by Perry et. al. on March 16, 2001, and U.S. Patent Application 09/809,682

"System and Method for Converting Range Data to 3D Models," filed by Frisken

et al. on March 16, 2001.

Here, we describe a system and method where ADFs are used to model the

interaction between deformable objects. ADFs have several advantages for

modeling impacts between objects. These advantages overcome problems present

in prior art modeling systems. These advantages include compact representations

of complex surfaces, direct inside/outside and proximity tests, fast localization of

potential contact regions, more accurate representation of the overlap region, and

methods for computing material-dependent contact deformation.

System Overview

Figure 1 shows our method and system 100 for modeling physical interactions

using adaptively sampled distance fields. In the most general case, the input to the

method 100 includes at least two models 101 representing graphics objects or

physical systems, and generation parameters 102. The input models 101 can be

constructed using any known modeling technique. For example, the models can be in the form of range images, point clouds, triangle meshes, or implicit functions.

Because the models can be in many forms, our method is particularly suited for
5   animation and physical modeling where many different model forms are often used in conjunction depending on production cost and time requirements, and available technologies. As an advantage, the models 101 can uses different representations. For example, one model can be derived from range images, and the other model can be in the form of a polygon mesh.

10   In step 110, ADF-A and ADF-B 103 are generated 115 according to the generation parameters 102. For example, the generation parameters 102 can specify a level-of-detail, or an acceptable error measure.

15   Step 120 indicates a next processing step, in time, as the models move relative to each other. For real-time modeling, the time steps can correspond to a frame rate 121, e.g., 30 frames per second. For real-world physical simulations, for example, atomic interactions, or climatic and astronomic simulation, the time steps can range from fractional seconds to years or light-years.

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Detecting Collisions, Penetration, and Proximity

Step 130 determines the relative position of the models with respect to each other. More specifically, a determination is made whether any portions of the models 103
25   overlap each other. The sign of the distance values reconstructed from the ADFs 103, at any point in space, provides a convenient inside/outside test.

The spatial data structures of the ADFs can be exploited to quickly locate a potential region of overlap 131. For example, if the spatial data structures of the ADFs are octrees, bounding boxes of the octree cells can be intersected to determine the overlapping region. If the overlapping region is non-empty, a

5   potential collision has occurred.

In addition to the bounding boxes of the ADF cells, the distance values at the root cell of the ADF, and subsequent children cells of the root cell in the hierarchy of the ADF, can be used to exclude the possibility that objects are interacting.

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For example, if the distance values at the root cell of an object A indicate that the nearest surface of object A is 2 units away, and the distance values at the root cell of an object B indicate that the nearest surface of object B is also 2 units away, and the measure of overlap between the root cells of object A and object B is very

15   small, say 1/8 of a unit, then the present invention can conclude no interaction between object A and object B can occur.

This is an advantage of the present invention and unlike the prior art methods where distance information is not available. The use of distance values to exclude

20   the possibility that objects are interacting can be used at any level in the ADF spatial hierarchy, not just at the root cell. When there are thousands of objects in a scene interacting, this advantage of the invention can dramatically reduce the processing time required.

25   In the case where the overlapping region 131 is non-empty during the current time step 120, an interaction procedure 140 is invoked to produce ADF-A$'$ and ADF-B$'$ 104 using interaction properties 141.

The interaction procedure 140 can be a deformation procedure, in which case, ADF-A' and ADF-B' 104 are deformations of ADF-A and ADF-B 103, and the interaction properties 141 are material properties. Then, ADF-A' and ADF-B' 104, the deformed shapes of ADF-A and ADF-B 103, can be used in the next time step, or they can be used as initial deformations of the models in a physical simulator.

In one embodiment as shown in Figure 2a, the interaction procedure 140 is an identity procedure, and an intersection ADF, ADF-C 105, is generated. Interaction forces acting on the intersection ADF ADF-C 105 can be determined, as described below.

To determine proximity of the two models, the intersection ADF ADF-C 106 can be generated from offset surfaces as shown in Figure 2b. In this case, the models interact with each other even though they do not physically overlap. For example, for certain interaction properties, such as force fields, the models can interact with each other at a distance, prior to physical contact.

Determining Forces

There are a number of methods for determining the forces acting on two bodies depending on the interaction properties 141, see Witkin et al., "*An introduction to physically based modeling*", SIGGRAPH Course Notes 32, ACM SIGGRAPH, 1994.

Penalty-based methods determine the forces based on how far objects penetrate each other during a discrete time step. Distance fields have been used to determine

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penetration depth at sample points along the penetrating surface as well as to compute contact forces, see Frisken-Gibson, "*Using linked volumes to model object collisions, deformation, cutting, carving, and joining,*" IEEE TVCG, pp. 333-348, 1999, and Hoff et al., "*Fast and simple 2D geometric proximity queries using graphics hardware,*" Proc. Interactive 3D Graphics'01, 2001.

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As shown in Figure 3, a force vector F_B acting on object B due to penetration by object A is approximated by the sum of forces f_{Bi} 301-308, so that $f_{Bi} = k_A(x_i)$ * $dist_A(x_i)$ * $g(x_i)$, where $k_A(x)$ is a material stiffness of A at x, $dist_A(x)$ is a closest distance from x to the surface of S_A of A, and $g(x)$ is a normalized gradient vector of A's distance field at x.

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The intersection ADF-C 105, according to the invention, represents the volumetric overlap region 131 to a high precision. Prior art penalty methods typically determine F_A from a small number of points at the penetrating surface.

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As an advantage of ADFs, penetration forces can be determined over the surface, or the **entire volume** of the overlap region. Forces can be determined at an arbitrary number of well-spaced sample points seeded on the surface, or throughout the entire volume. Because the distance field of each cell of an ADF is represented by an analytically defined field, it is also possible to analytically interpolate forces throughout the entire overlap region. These advantages of ADFs provide the opportunity to determine impact forces more accurately than prior art methods.

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Determining Contact Deformation

On contact, the models can be deformed according to the forces. Various methods can be used to combine distance fields and achieve material dependent

5   deformation, see Desbrun et al. *"Animating soft substances with implicit surfaces,"* Proc. SIGGRAPH'95, pp. 287-290, 1995, and Cani-Gascuel *"Layered deformable models with implicit surfaces,"* Proc. Graphics Interface'98, pp. 201-208, 1998.

Alternative Embodiments

10   Figures 4, 5, and 6 show detailed embodiments for the interaction procedures 140, which compute forces and deform the ADFs 103 representing the models 101. As shown in Figure 4, step 410 generates the ADF-C 419 representing the overlap regions 131 using generation parameters 411. The generation parameters include a

15   distance function that reconstructs distance values in each of the ADFs 103, and then determines minimum distance values between the reconstructed distance values.

Step 420 computes forces 429 from the ADF-C 419 by surface sampling, volume

20   sampling, or analytical integration of the interaction, e.g., material, properties, as described above. Then, a physical simulator 430 can be used to modify the ADF-A and ADF-B 103 according to the forces and proceed with the next time step 120.

As shown in Figure 5, step 510 respectively generates new cells for ADF-A' and

25   ADF-B' 104 according to the interaction properties 141, e.g., material properties, of ADF-A and ADF-B 103 and the deformation procedure. The deformation procedure determines new distance values at specified location using the original

distance values and gradients of the distance field. Step 520 constructs ADF-A'
and ADF-B' 104 at requested locations to reflect the deformation, and proceeds
with the next time step 120.

5   As shown in Figure 6, step 610 respectively generates new cells in ADF-A' and
ADF-B' according to the material properties 141 of ADF-A and ADF-B and the
deformation procedure. The deformation procedure determines new distance
values at specified location using the original distance values and gradients of the
distance field. In step 620, the deformed shapes of ADF-A' and ADF-B' 104 are

10   input as initial deformations to a physical simulator 620 to speed up the processing.
The physical simulator 620 then produces the deformed ADFs 103 and proceeds
with the next time step 120.

This invention is described using specific terms and examples. It is to be

15   understood that various other adaptations and modifications may be made within
the spirit and scope of the invention. Therefore, it is the object of the appended
claims to cover all such variations and modifications as come within the true spirit
and scope of the invention.